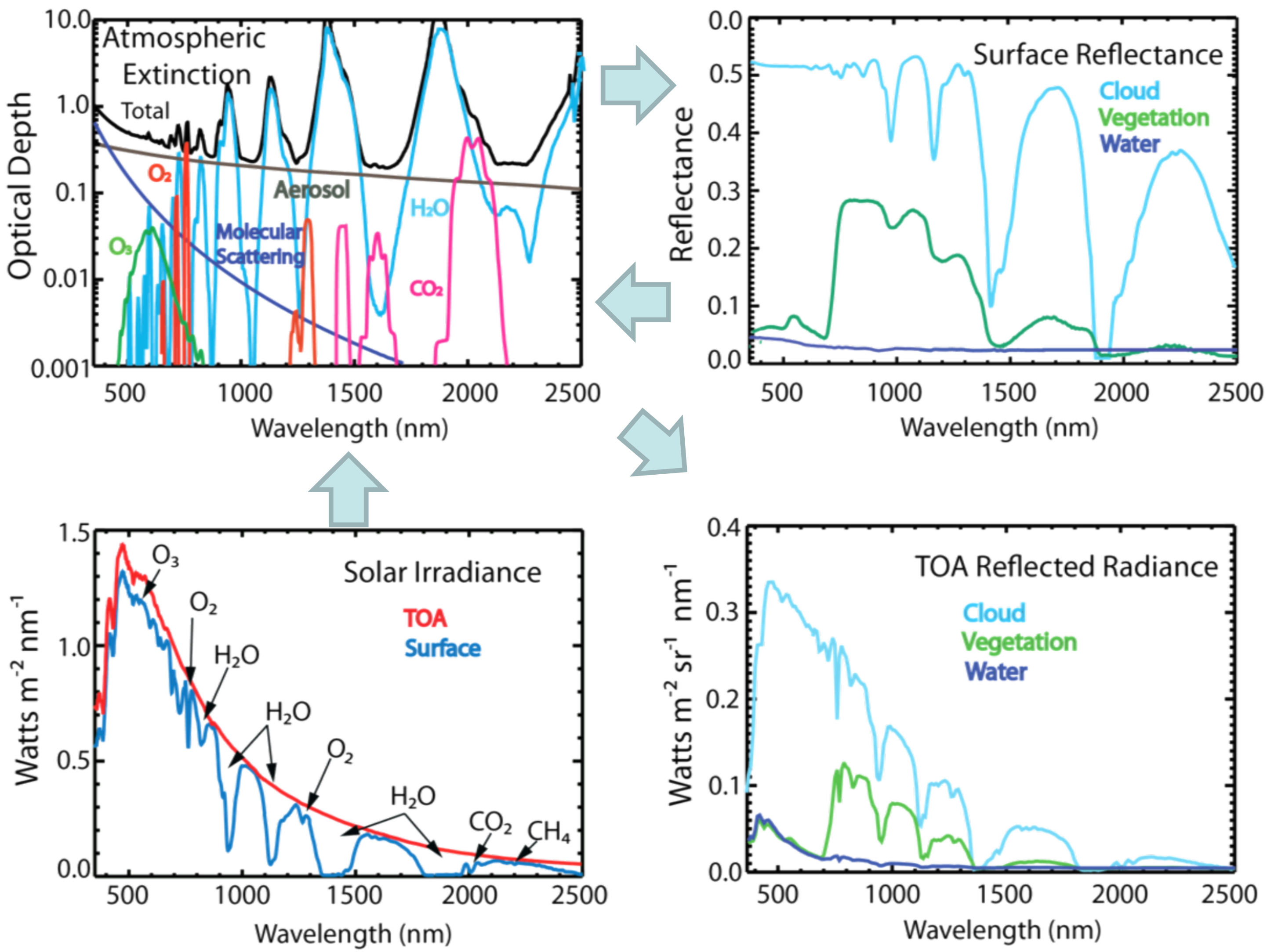
New Methods of Spectral Decomposition for Source Separation and Trend Analysis of Reflected Shortwave Radiation

Logan Wright, Odele Coddington, Bruce Kindel, Peter Pilewskie

Laboratory for Atmospheric and Space Physics,

University of Colorado, Boulder, CO USA

Spectral *Un-mixing*

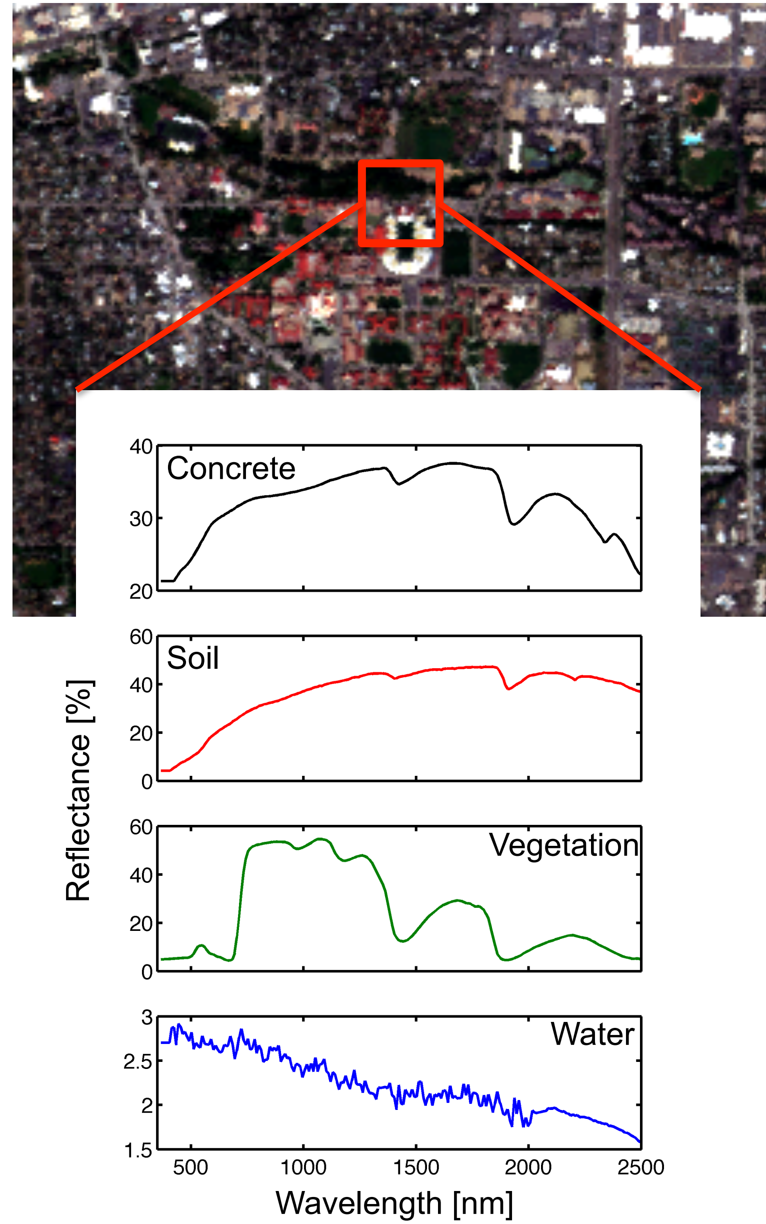


What is source separation?

Measured signals include contributions from:

- Different surface types
- Atmospheric sources: absorption by gases, aerosols and clouds.

Goal: identify the physical origin and the magnitude of these signals



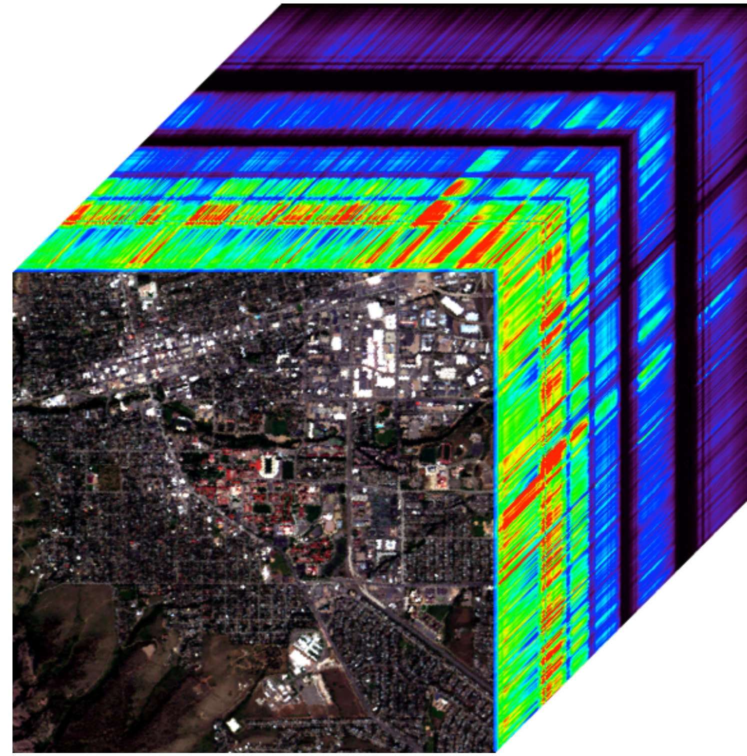
Possible source reflectance spectra for surface types in the red outlined region

Motivation

Hyperspectral Imagers:
- produce large data volumes
- resolve spectral and spatial features

Model based source separations introduce model biases
- "Atmospheric Correction" methods focus on extracting surface reflectance

Existing numerical methods often produce non-physical results
- Principal Component (PCA) or Independent Component Analysis (ICA)
- Usually use atmospherically corrected reflectance as input data



Hyperspectral Image Cube from AVIRIS centered on the University of Colorado Boulder Campus

Atmospheric Correction

- A *source separation* focused on surface reflectance
- Model based.
- Generally not focused on retrieving atmospheric properties
- Can be problematic for aircraft
  - ➢ No knowledge of atmosphere above sensor
  - ➢ Even thin cloud or aerosol layers can cause large errors in retrieved surface reflectance

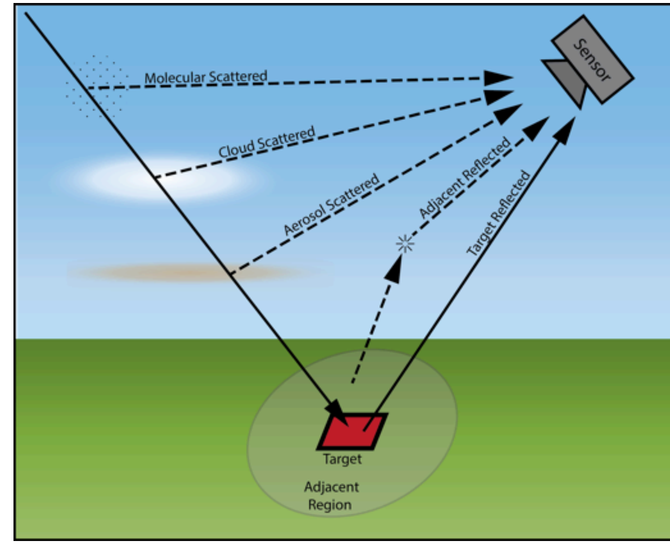
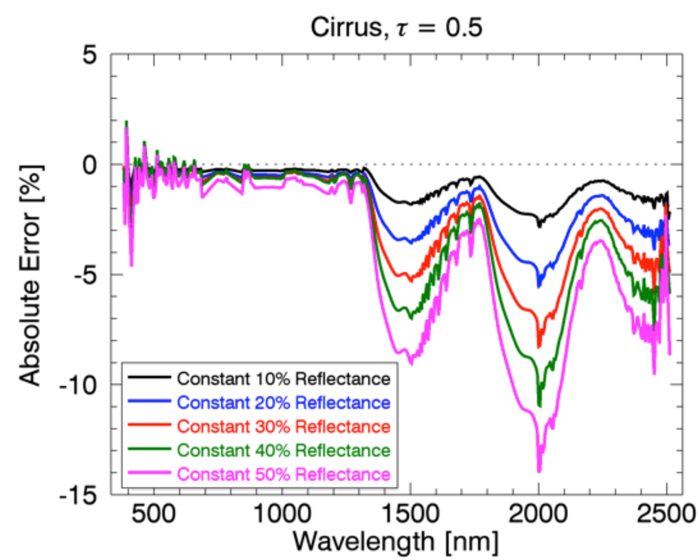


Diagram above shows atmospheric and surface contributions to the signal observed at an air- or spaceborne instrument.

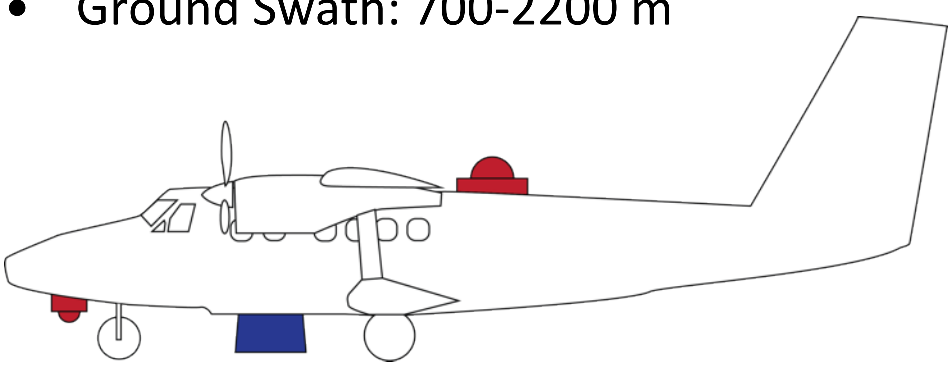


Absolute error in retrieved surface reflectance from an atmospheric correction algorithm below a thin cirrus cloud.

NEON Imaging Spectrometer (NIS)

- 426 wavelength bands, from 380 to 2510 nm
- Spectral Sampling: 5 nm
- Spectral Resolution (FWHM): 5.6 nm
- Pushbroom Detector Geometry
- Flight Altitude: 1-3 km
- Ground resolution: 1-3 m
- Ground Swath: 700-2200 m

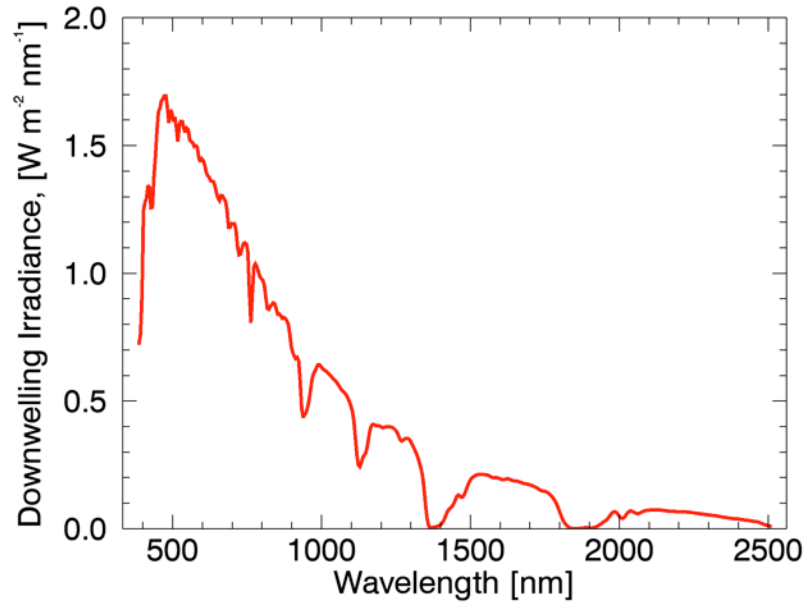
NIS flight tracks at 1 m resolution overlaying AVIRIS 18 m imagery [*Kampe et al., 2013*]



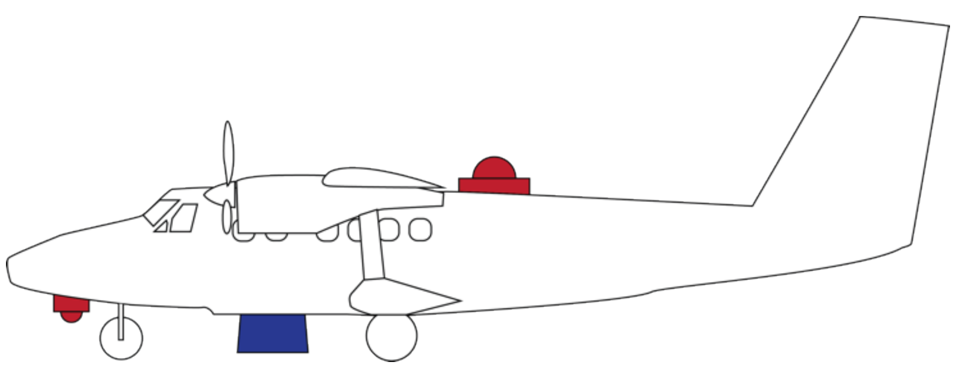
[*Johnson et al.*, 2010a, 2010b and *Kampe et al.*, 2010a]

Solar Spectral Irradiance Radiometer

- Dual spectrometers cover 350-2150 nm
- Silicon Detector Array: 350-1100 nm
- InGaAs Detector Array: 900-2150 nm
- Nadir and zenith viewing
- Zenith stabilizing platform offsets aircraft attitude.

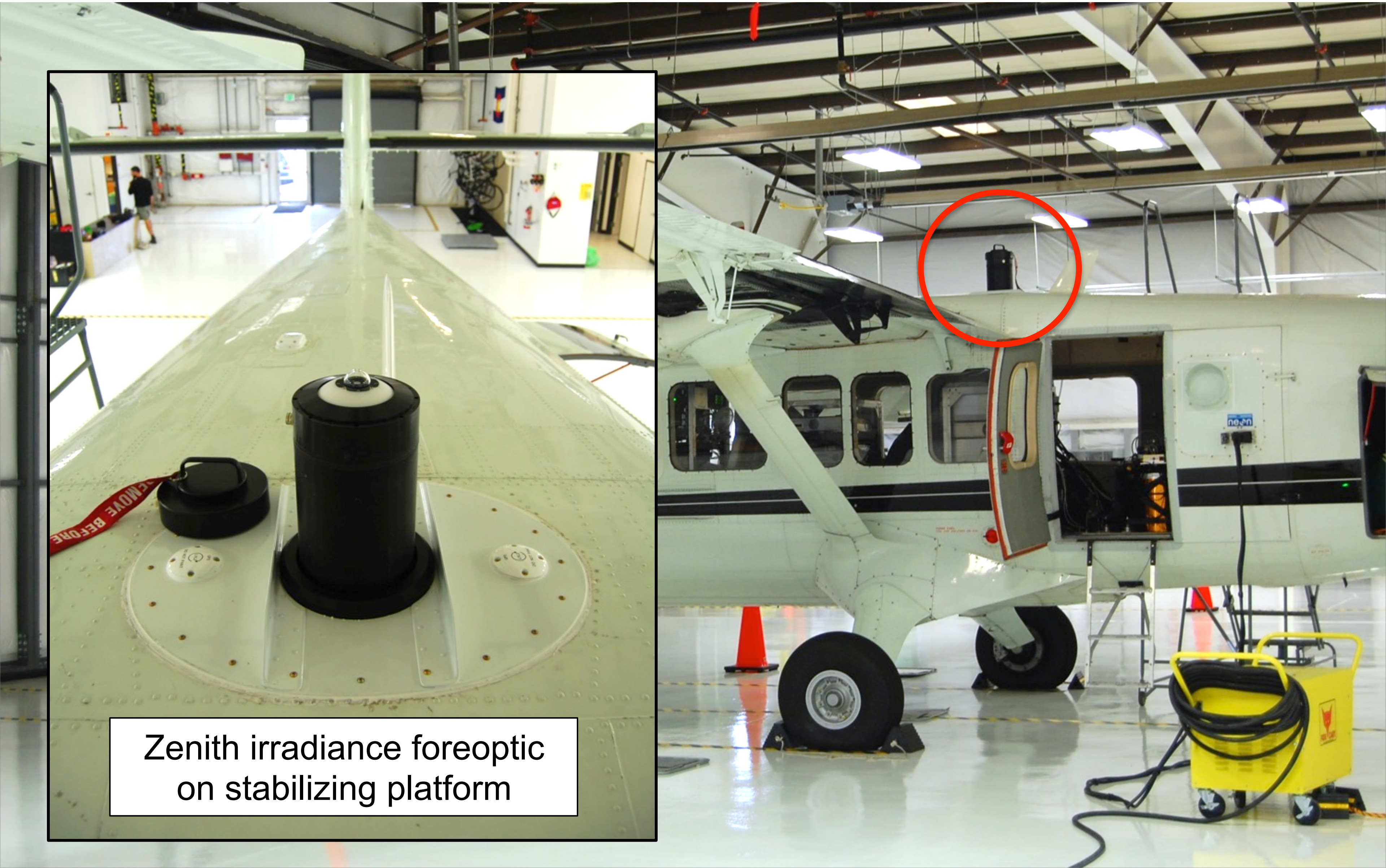


Downwelling irradiance under cloud-free atmospheric conditions



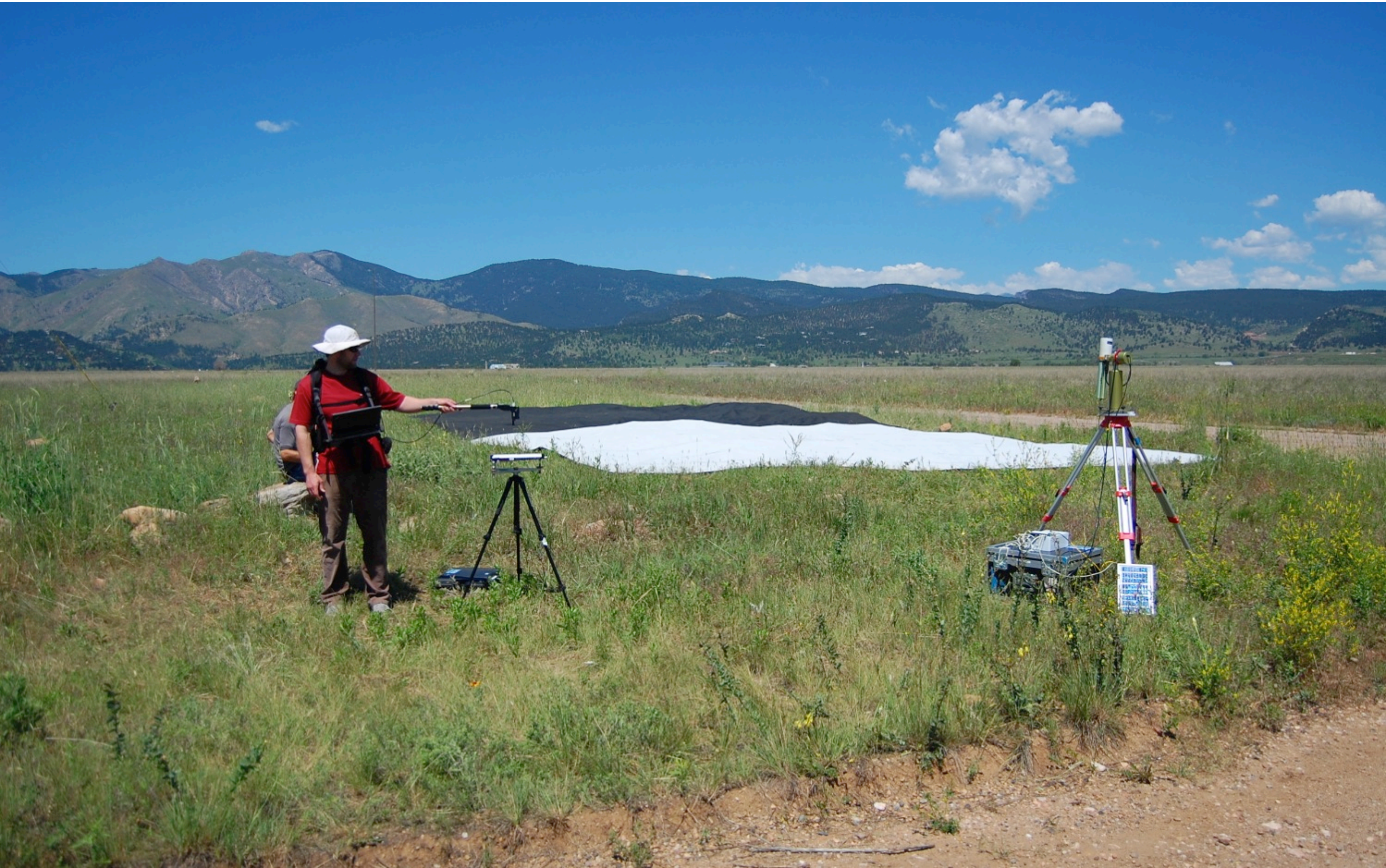
[*Pilewskie et al.*, 2003]

NEON Test Flight Campaign

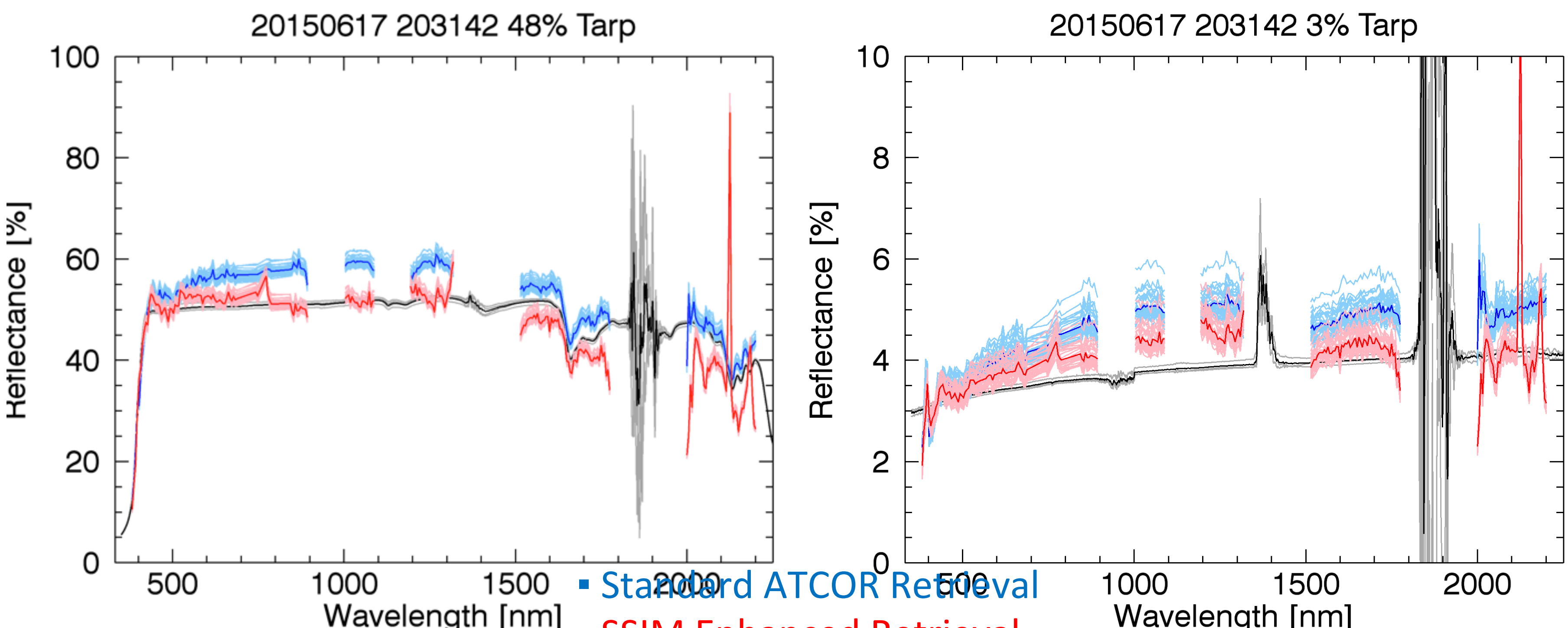


Zenith irradiance foreoptic on stabilizing platform

NEON Test Flight Campaign



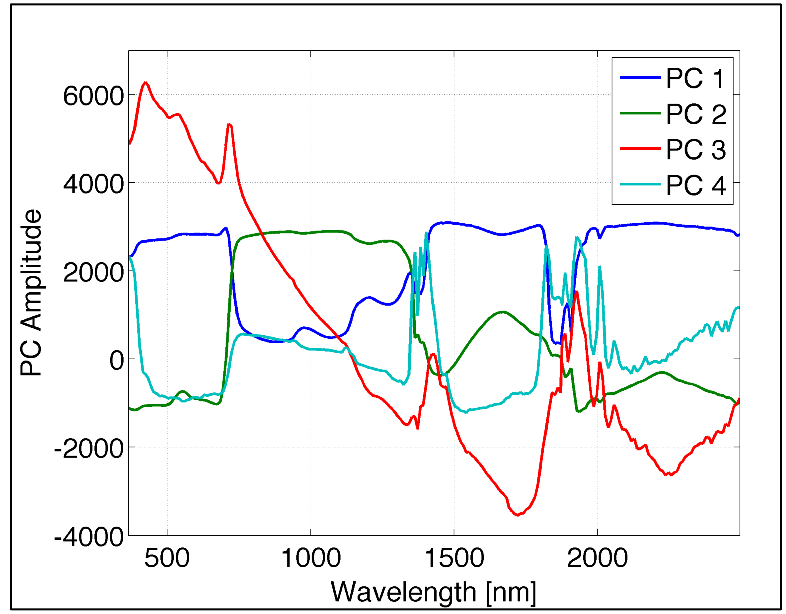
Cirrus and Scattered Cumulus



- Standard ATCOR Retrieval
- SSIM Enhanced Retrieval

Numerical Methods

- Methods such as PCA and ICA have been widely used
  - ➢ Have no basis in physics
  - ➢ Separation is purely statistical
- Can produce non-physical, negative results
- Difficult to interpret



Principal Component Analysis of a hyperspectral image.

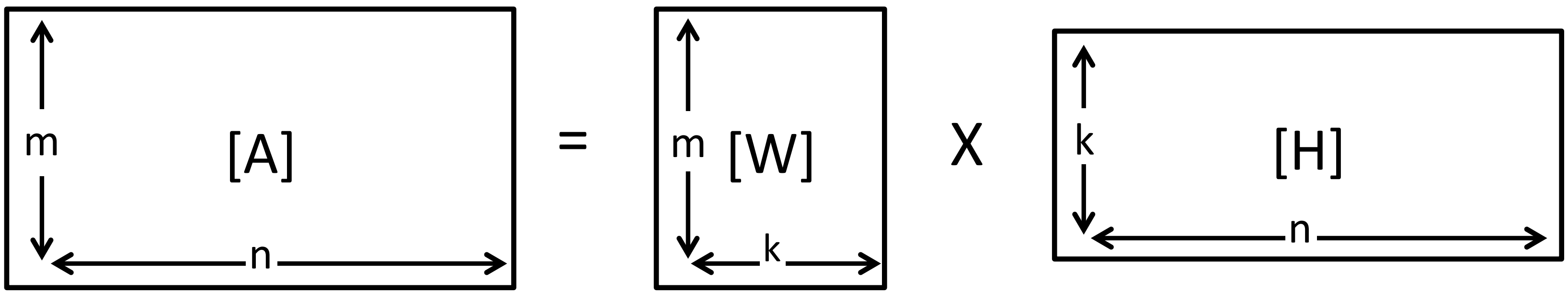
- **Vegetation signal is split into two components with opposite signs. (Green and Blue)**
- **Three of the four principal components cross 0**

Non-negative Matrix Factorization (NMF)

- Most common implementation was first published by Lee and Seung (2001)
- Used in the machine learning community and with mass spectrometry.
- Comparison with existing methods:
  - Pros:
    - Non-negativity.
    - No inherent constraints.
    - Allows for the introduction of additional user-defined constraints.
  - Cons:
    - Solution is highly dependent on initialization.

NMF Method

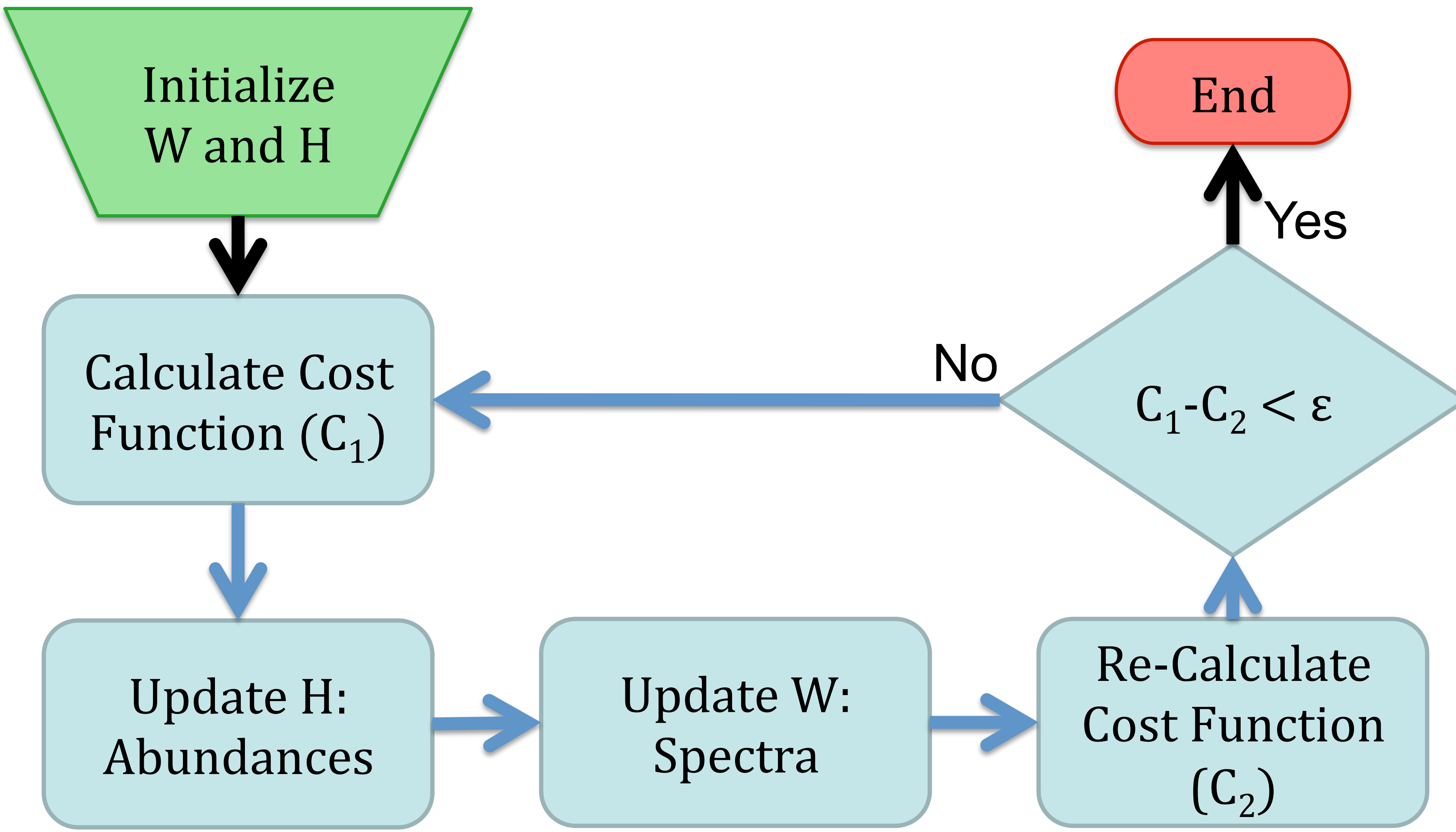
- Spectral decomposition method



- Decomposes an original hyperspectral image, **A**, of *m* wavelengths by *n* pixels to *k* number of endmembers
  - To spectral endmembers, **W**, of dimensions m-by-k
  - To spatial abundances, **H**, which has dimension k by n pixel

- Decomposition is produced by minimizing the difference between the original data and the reconstructed **WH**

NMF Workflow



Informed NMF for Source Separation

Use the calibrated at-sensor radiance:

- Includes surface, atmosphere and solar contributions.
- Avoids introducing errors from the atmospheric correction model.

Introducing constraints allows NMF to be tailored to hyperspectral imagery:

- Introduce knowledge of the physics of hyperspectral imagery into the NMF solutions.
- Guide the method to realistic separations.

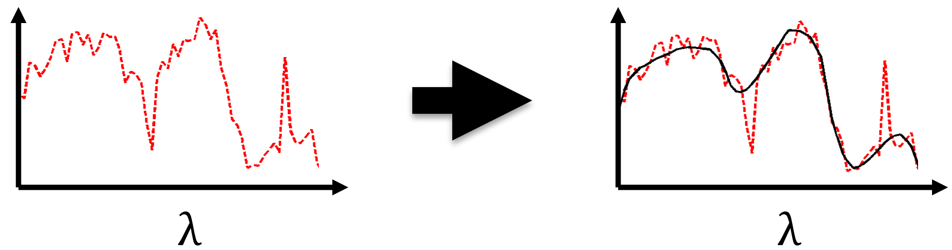
Use knowledge of realistic source types to produce an initial separation guess.

- Physically realistic initial guess improves the NMF solution.

Constraint: Smoothness

Spectral: Smoothness is a general property of spectra at the resolution of hyperspectral instruments (5-10 nm sampling and 5-10 nm fwhm)

Example of spectral smoothing:

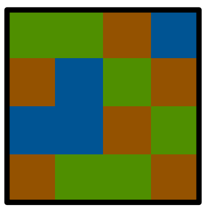


Spatial: Real scenes vary smoothly with some discontinuities such as sharp manmade boundaries or land/water transitions

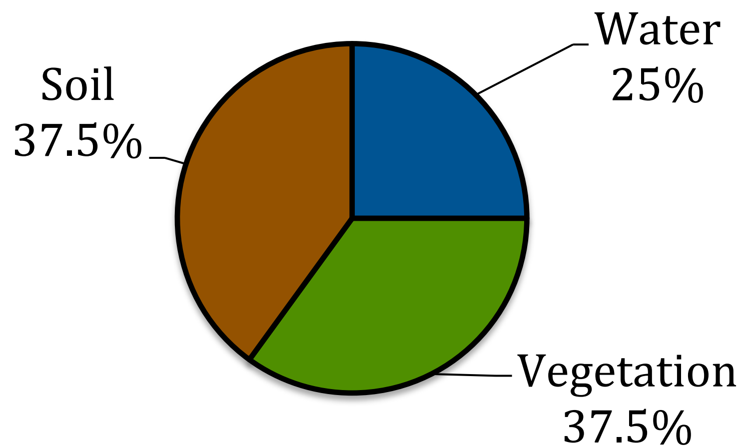
Piecewise smoothness constraints were enforced in both the spatial and spectral NMF decomposition to capture these properties

Constraint: Abundance Sum-to-One

Abundances are calculated such that they represent the "fractional abundance" of each endmember in the pixel.



One Pixel -
Composed of a
mix endmembers

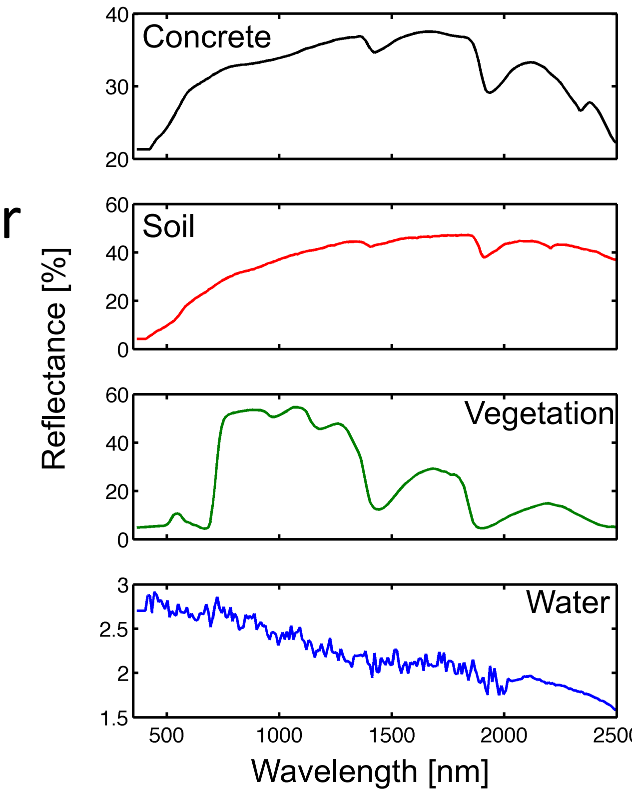


End result is more interpretable result and improved separation of endmembers

Initialization

Use library spectra as initial separation guess

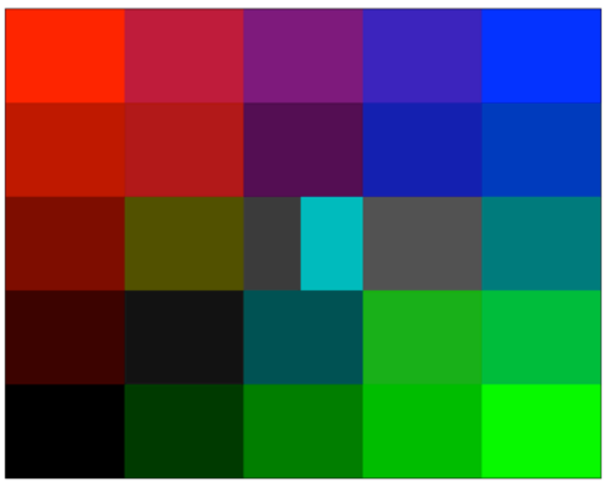
- Provides a realistic starting point for NMF algorithm
- Improved separation over the random initialization that is commonly used

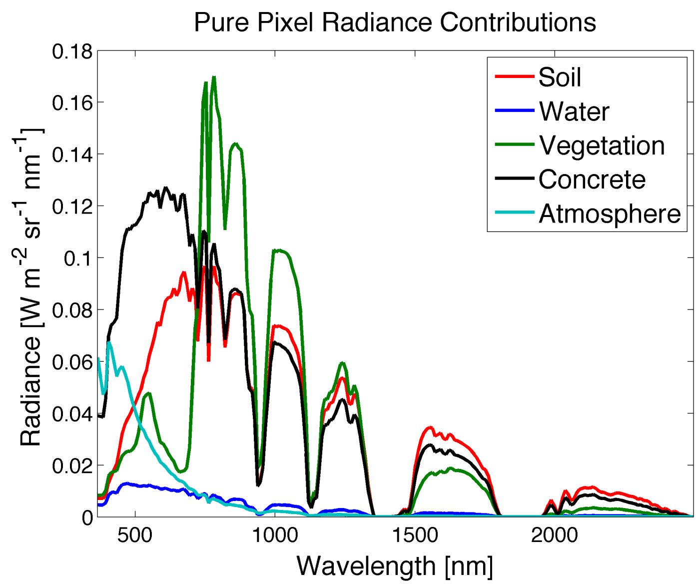


Sample ASTER Library Reflectance Spectra

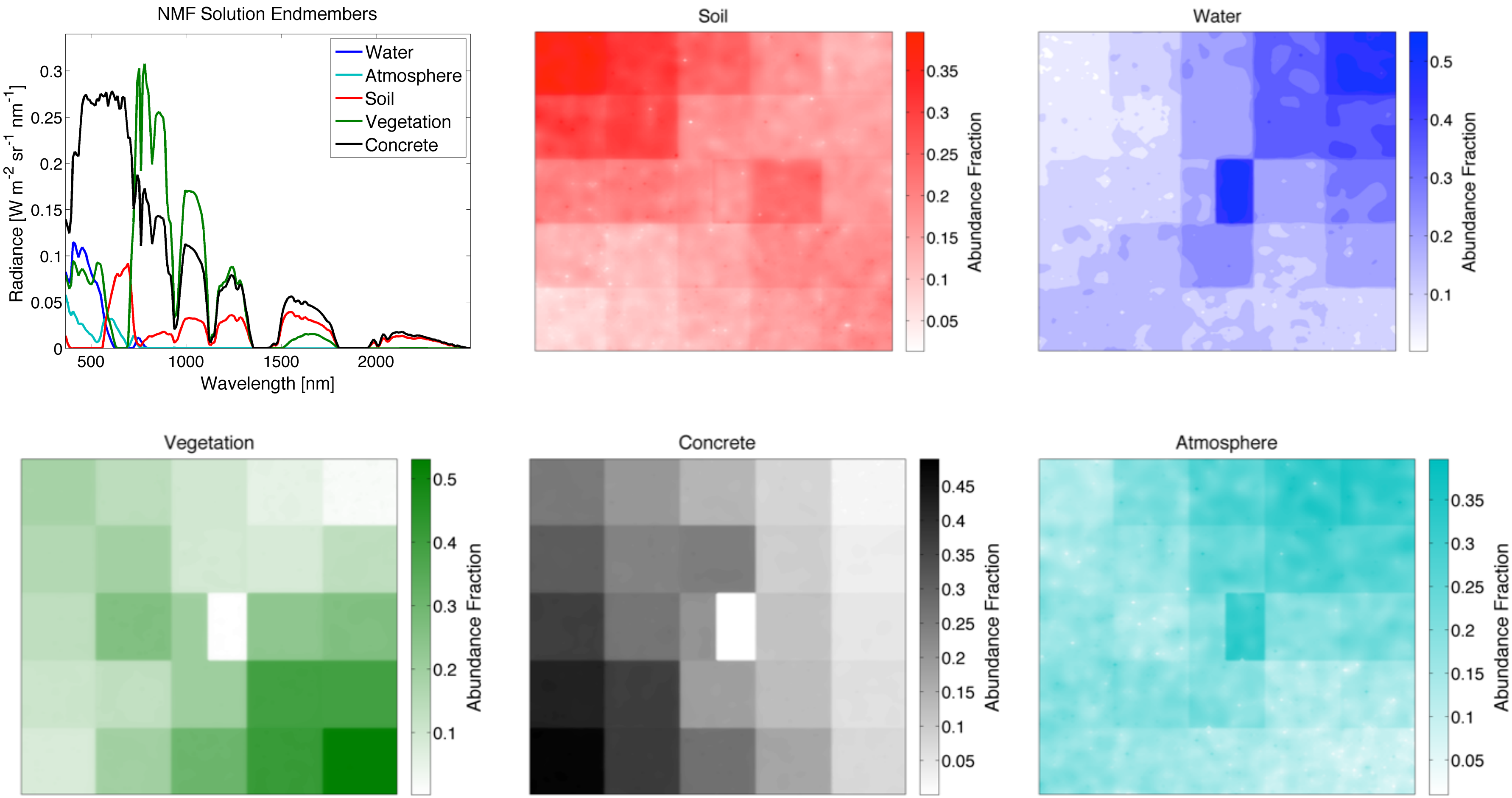
Informed NMF Results

- Simulated scene combines single source radiances to produce mixed source pixels and a whole scene



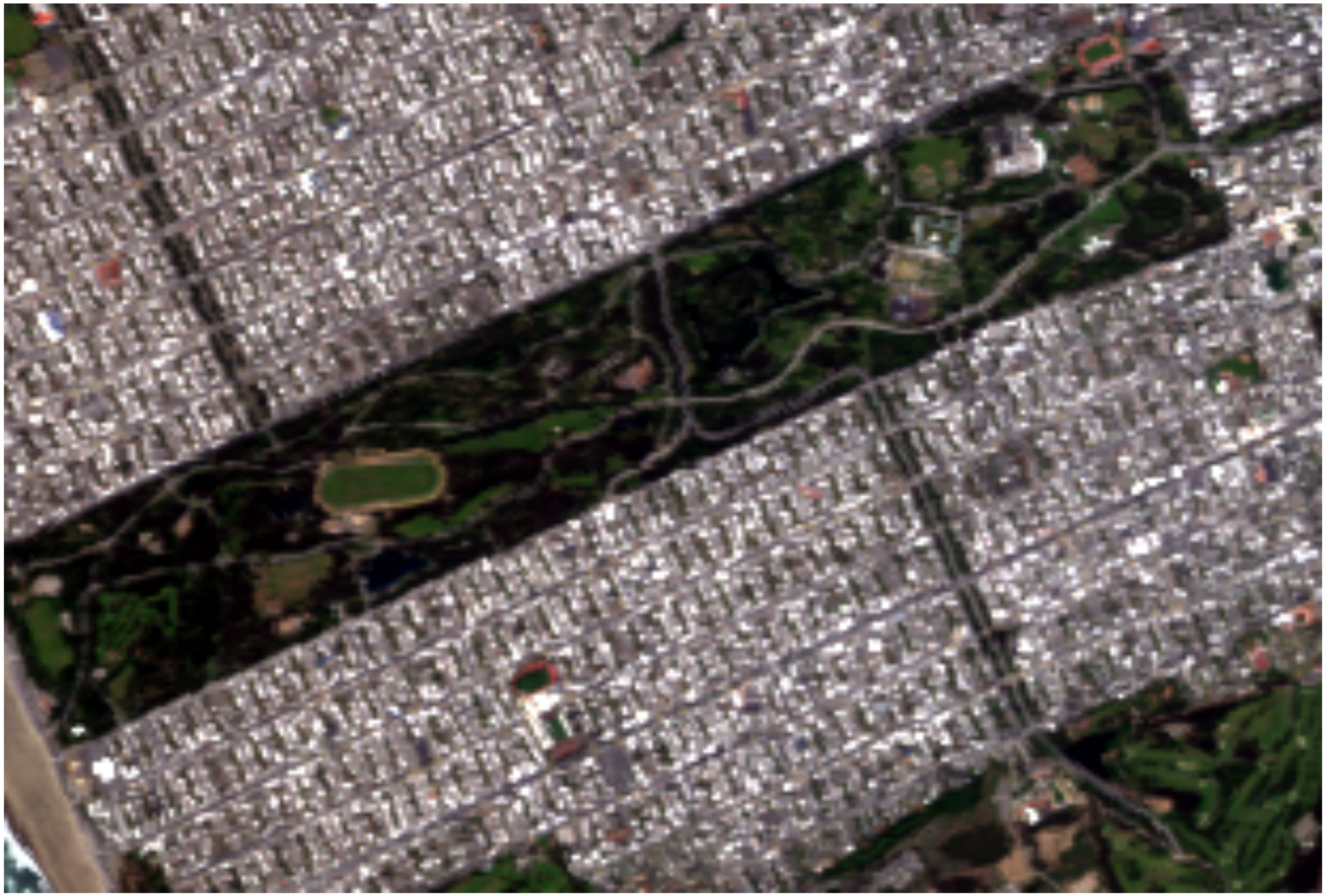


Simulated image, (above left): each color represents one of the four input surface types (above right). The center teal rectangle is a pure atmospheric contribution (zero surface reflectance). Corner pixels are pure surface types while other pixels are mixtures.

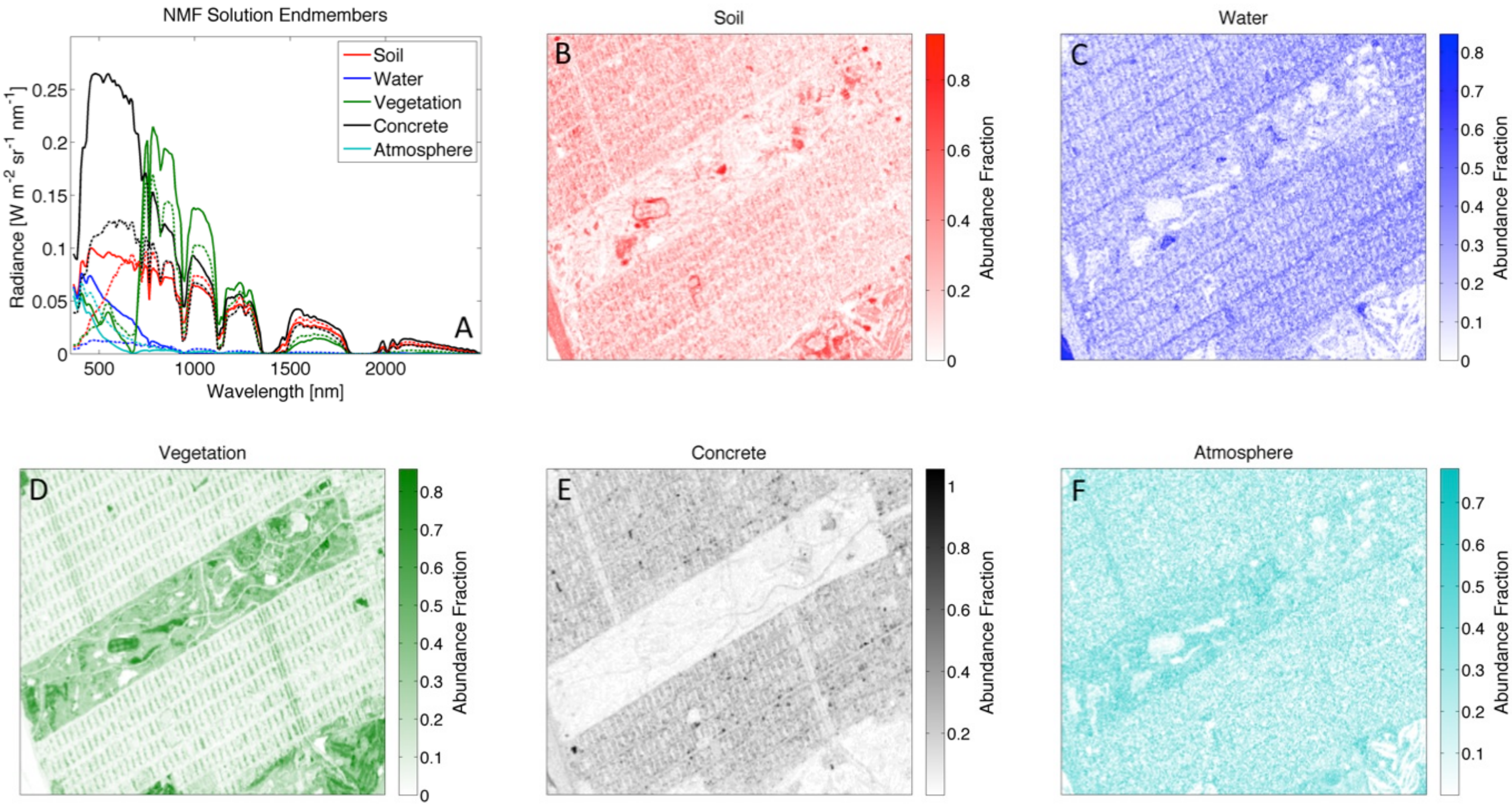


Results of the application of the informed NMF routine to the simulated scene from the previous slide. Figures show the resulting output spectral endmembers (top-left), and the corresponding spatial abundance fractions (remaining five figures).

Informed NMF Results



Real Color Image of Golden Gate Park, San Francisco CA: AVIRIS at-sensor radiance data of this same region was processed with the NMF algorithm. Region was chosen as it includes a wide variety of surface types from open water to man-made buildings and vegetation.



Results of the application of the informed NMF routine to an AVIRIS scene of Golden Gate Park in San Francisco, CA. Panel A shows the resulting output spectral endmembers (solid) and their corresponding initial guesses (dashed). Panels B through F show the spatial abundance fractions corresponding to the five endmembers in panel A.

Informed NMF Conclusion

- How well did it work?
  - Endmember spectra resemble physically independent sources
  - Abundance maps correctly highlight regions of strong contributions
  - Sources with distinct spectral shapes, like vegetation, are more reliably separated
- Areas for Improvement?
  - Library spectra reduce dependence on initial guess
  - Sources with similar spectral shapes, are poorly separated; pure pixels are retrieved as mixtures
  - Water and atmosphere are especially difficult to differentiate
  - Where one endmember is large, other endmembers may have falsely low values (See 700-1300 nm region of vegetation and soil in the simulated scene)

Hyperspectral Imager for the Coastal Ocean (HICO)

Current work is using hyperspectral data from the HICO instrument on the International Space Station.

- 380-960 nm sampled at 5.7 nm.
- 90 m spatial resolution

Data covers a wide variety of scene types (focused on coastal ocean regions)

This analysis focusing on two scene types:

- Clear scenes (left)
- Thin cloud scenes (right)